The GPS Occultation Sensor for NPOESS

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***Abstract*- The Global Positioning System Occultation Sensor (GPSOS) is a precision GPS instrument carried by the NPOESS spacecraft. It measures primarily the electron density profile and scintillation parameters of the ionosphere. The measurements are obtained by tracking signals of GPS satellites that are observed to rise or set through the atmosphere while recording the signal amplitude and phase.**

I. Introduction

Radio occultation techniques were originally developed for studies of the atmospheres of other planets in the solar system. The application to the Earth's atmosphere, using the Global Positioning System (GPS) as radio signal sources for a receiver on a satellite in Low Earth Orbit (LEO), was first demonstrated by the GPS/MET experiment [1,2]. The technique provides a method for global scale monitoring of ionosphere electron density profiles and scintillation properties, as well as temperature, pressure and humidity profiles in the troposphere/stratosphere.

The GPSOS has been developed for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) under the direction of the NPOESS Integrated Program Office (IPO). The NPOESS satellites will be positioned in near-polar orbits at 833 km altitude. The GPSOS builds on heritage from the GNSS Receiver for Atmospheric Sounding (GRAS) [3] which is developed and produced for the Eumetsat Metop satellites. The GPSOS has an extended atmosphere altitude coverage (0-800 km), for monitoring of the ionosphere, as compared to Metop-GRAS (0-80 km).

II. Measurement Principle

When a precision GPS receiver on board a LEO satellite tracks a GPS signal that is observed to rise or set through the atmosphere, the arrival time of the received signal is delayed because of the refractive bending and of the slowing as it crosses the atmosphere, see Fig. 1.

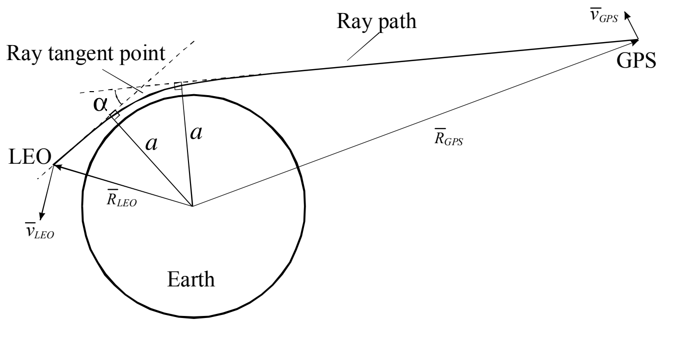

Fig. 1. Radio occultation geometry showing refractive bending angle α.

By measuring the signal code and carrier phase delay on two different frequencies during the occultation of the GPS satellite, the ionospheric total electron content along the ray can be determined as a function of altitude. From this data it is possible to retrieve the vertical electron density profile as well as the neutral atmosphere refractive index profile.

An example of the global distribution of occultation measurements during one day for a single GPSOS instrument is shown in Fig. 2.

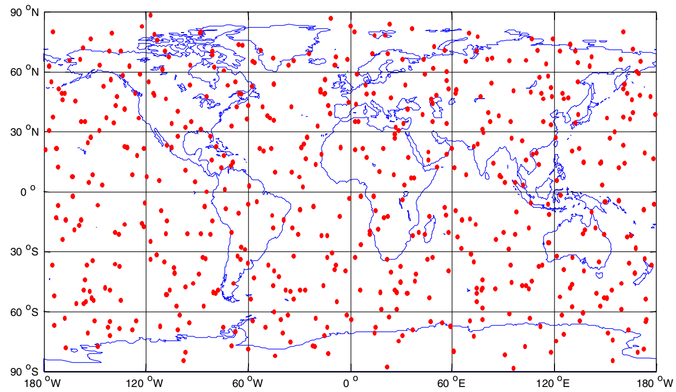

Fig. 2. Distribution of measurements during 24 hours.

III. Instrument Overview

The basic function of the GPSOS instrument is to receive RF signals emitted by GPS satellites when these signals pass through the atmosphere. The signals on both the L1 and the L2 frequency are acquired, tracked, and demodulated. The anti-spoofing (encryption) of the P-code on the L2 frequency is mitigated by the use of codeless tracking techniques. The demodulation process is carefully designed to cope with low signal power levels and wide signal dynamics. An ultra-stable oscillator with a frequency stability of $<10^{-12}$ (3 - 100 s) is used to generate the instrument phase reference and the L1 and L2 signals are sampled at a rate of 100 Hz.

Measurements of this kind are referred to as occultation measurements. The signals of the occulting satellites are received through two identical occultation antennas, one dedicated to the rising occultations and one dedicated to the setting occultations, see Fig. 3. The occultation antenna is designed with antenna gain patterns optimized to cover an azimuth angle range of +/- 50 degrees and an altitude range of 0-800 km for the ray tangent point.

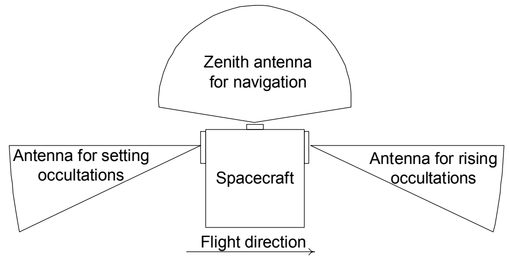

Fig. 3. GPSOS antenna configuration on spacecraft.

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The instrument also receives GPS signals via a third zenith pointing antenna with a wide conical coverage. It acquires and tracks GPS signals as required for the real-time navigation used by the instrument to control its operation. Dual-frequency zenith measurements are also used for measuring electron content of the ionosphere above the orbit altitude.

An RF Conditioning Unit is connected as close as possible to each of the three antennas to minimize system noise due to cable losses. It contains several levels of filtering for rejection of on-board interference, low-noise amplification, and frequency down conversion.

The instrument comprises eight dual-frequency signal channels for occultation measurements and eight channels for navigation. The GPSOS instrument hardware has a nominal mass of 30 kg and a power consumption of 40 W. The GPSOS Engineering Development Unit (EDU) is presently under manufacturing for delivery to NPOESS in 2003. The already produced Metop-GRAS hardware is shown in Fig. 4.

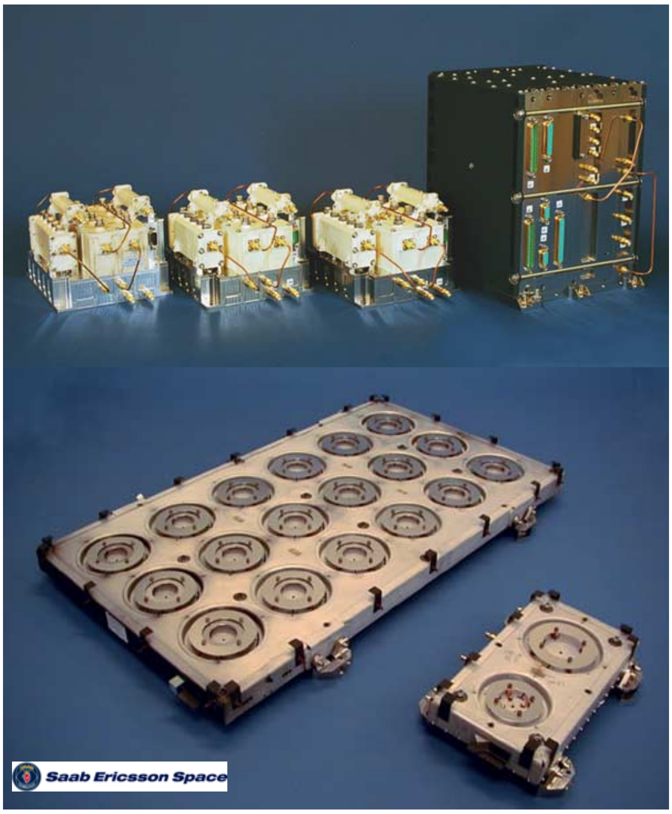

Fig. 4. RF Conditioning Units (top left) , Electronics Unit (top right), Occultation Antenna (bottom left), and Zenith Antenna (bottom right).

IV. ELECTRON DENSITY MEASUREMENTS

The performance of the GPSOS instrument is specified in terms of the measured geophysical parameters. The primary Environmental Data Records (EDRs) are parameters of the ionosphere. The electron density EDRs comprise the Total Electron Content (TEC), the electron density as a function of height, the specific height of the F2 peak, HmF2 and of the E-layer, HmE, both identified from the retrieved profile of electron density.

The basic measurement is the TEC of the occultation link. This is denoted satellite-to-satellite TEC (or SS-TEC). The SS-TEC is derived from the dual-frequency combination on the measured carrier phase [4] and calibrated using the pseudo-range measurements of both the occultation and navigation links. The GPSOS specified SS-TEC measurement accuracy is 3 TECU (1 TECU = 10^{16} electrons/m^2).

The electron density profile is derived from the SS-TEC through the calculation of the bending angle and subsequently inverted using the Abel transform assuming local spherical symmetry [4]. The bending angle is proportional to the time derivative of the SS-TEC and hence do not need calibrated TEC as input. Further the bending angle as function of impact height is extrapolated above orbit height in the integration of the Abel transform. The specified accuracy of the electron density profile is maximum of 3×10^{11} electrons/m^3 or 20%, the dominant error source being the horizontal gradients in the ionosphere. The geometry of each occultation can roughly be categorized in terms of the azimuth angle, which is defined as the angle between a plane defined by the occultation ray paths and the velocity vector of the NPOESS satellite. Small azimuth angles imply smaller errors in the retrieved electron density. The vertical resolution of the electron density profile is 2 km, corresponding to the diffraction limit, and obtained using a sampling rate of 1Hz through the ionosphere.

Fig. 5 shows a recently measured electron density profile using the Danish research satellite Ørsted capable of GPS occultation measurements. This electron density profile is from February 20, 2002 and part of a campaign to measure the ionosphere cusp region using satellite data from CHAMP, SAC-C and Ørsted combined with radar measurements from ground at Svalbard and Tromsø (Norway). The two measurements are located less than 300 km apart and a close agreement between the Ørsted profile and the digisonde is observed.

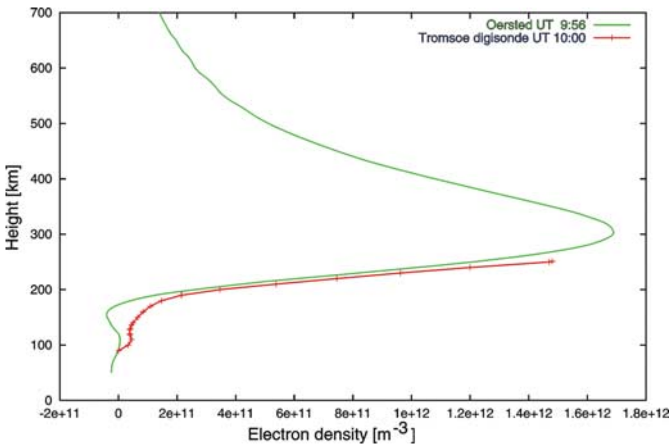

Fig. 5. Ionosphere occultation from February 20, 2002 compared against a digisonde measurement. Distance between the tangent point of the Ørsted profile and the digisonde is about 300 km.

The geometry of this particular occultation in Fig. 5 is favorable, with an azimuth angle less then 5 degrees, but still a small negative bias is seen for heights below 200 km. The sampling rate of this occultation is only 0.1 Hz resulting in a rather course vertical resolution of about 20 km, but still a E-layer is identified at HmE of approximately 100 km coinciding with the digisonde measurement.

The accuracy specifications for GPSOS measurements of HmF2 and HmE are 20 and 10 km respectively.

To overcome the assumption of local spherical symmetry the TEC measurements of both occultation links and GPS satellites tracked above orbit height can be combined in a tomographic solution of electron density to produce two-dimensional maps of electron density [5]. GPS occultation measurement can also be combined with ground based GPS observation both in a tomographic approach [6] or using data assimilation techniques as for the neutral atmosphere [7]. To make the optimal use of these new techniques of mapping and even predicting the state of the ionosphere the number of daily occultations need to be increased by e.g. having constellations of GPSOS instruments in different orbits.

V. IONOSPHERIC SCINTILLATION MEASUREMENTS

Ionospheric Scintillation is another primary EDR for GPSOS. The GPS signals received by the GPSOS instrument will experience rapid phase and amplitude fluctuations when propagating through the ionosphere during periods of scintillation. Scintillations are produced by changes in the phase velocity due to plasma-density irregularities in the ionosphere. The most severe scintillations are most likely to occur over the equatorial regions during evening hours. The GPSOS instrument will estimate the ionospheric scintillation parameters S4 and σ_ϕ, describing the rapid amplitude and phase fluctuations respectively, for one of the GPS frequency bands (L1). The sampling frequency will be 100 Hz. In order to estimate the parameter σ_ϕ, the background ionosphere effect on signal phase needs to be separated from the effect due to scintillations. This will be done in the ground processing using a detrending filter. Fig. 6 shows simulated Power Spectral Density functions for signal phase variations produced by a background ionosphere and scintillations. The figure illustrates that the detrending filter should have a cutoff frequency of approximately 0.1 Hz to best separate the two effects.

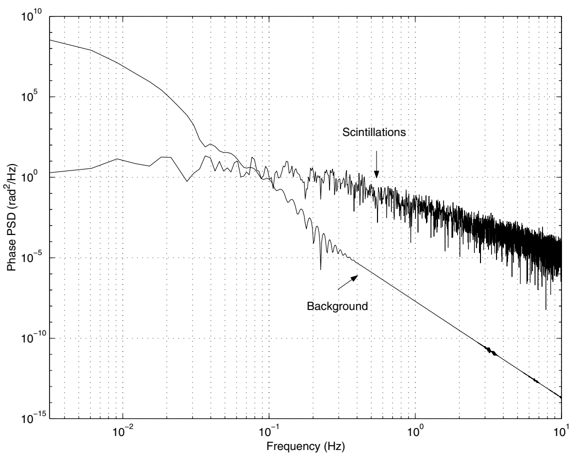

Fig. 6 Power Spectral Density functions for signal phase variations produced by a background ionosphere and scintillations.

VI. TROPOSPHERIC AND STRATOSPHERIC MEASUREMENTS

The GPSOS instrument also supports the retrieval of tropospheric and stratospheric properties including temperature, pressure, and humidity profiles by providing measurement data compatible with those generated by the Metop-GRAS instrument [3]. The atmospheric parameters can be derived from the retrieved refractive bending angles using a number of fundamental physical relations, such as the relation between refractivity and dry air density, the equation of state, and the assumption of hydrostatic equilibrium [4]. The GPSOS measurements of the neutral atmosphere can be used to produce more than 500 daily vertical temperature/pressure/humidity profiles per NPOESS satellite. Because of the limb sounding geometry, the temperature profiles have a fine vertical resolution (<1 km) with an estimated accuracy of 1K between 5 km and 30 km in height [4]. The most accurate data is obtained for altitudes of 10-20 km, where the estimated accuracy is 0.5 K. These data can significantly add to the number of vertical profiles obtained by radiosondes. In addition, the GPSOS occultation measurements are distributed globally covering regions not sampled by radiosondes, making the measurements very valuable for data assimilation into numerical weather prediction models (NWP).

REFERENCES

[1] E.R. Kursinski, G.A. Hajj, J.T. Schofield, R.P. Linfield, and K.R. Hardy, "Observing Earth's Atmosphere with Radio Occultation Measurements using the Global Positioning System", *J. Geophys. Res.*, Vol. 102, No. D19, 1997, pp. 23429-23465.

[2] G.A. Hajj and L.J. Romans, "Ionospheric electron density profiles obtained with the Global Positioning System: Results from the GPS/MET experiment", Radio Science, Vol. 33, No. 1, 1998, pp. 175-190.

[3] P. Silvestrin, R. Bagge, M. Bonnedal, A. Carlström, J. Christensen, M. Hägg, T. Lindgren, F. Zangerl, "Spaceborne GNSS Radio Occultation Instrumentation for Operational Applications", in Proceedings of ION GPS 2000, September 19-22, 2000, Salt Lake City, Utah, pp. 872-880.

[4] Høeg, P., Larsen, G.B., Benzon, H.-H., Grove-Rasmussen, J., Syndergaard, S., Mortensen, M.D., Christensen, J., Schultz, K., "GPS Atmosphere Profiling Methods and Error Assessments". Scientific Report 98-7, DMI, Copenhagen, 1998.

[5] Escudero, A., Schlesier, A., Rius, A., Flores, A., Rubek, F., Larsen, G.B., Syndergaard, S., Høeg, P., "Ionospheric Tomography Using Ørsted GPS measurements". *Phys. Chem. Earth*, 25 (2), 2001, pp.123-126.

[6] Rius A., G. Ruffini, & L. Cucurull, "Improving the vertical resolution of ionospheric tomography with GPS occultations", *Geophysical Research Letters*, Vol. 24, No. 18, 1997, pp 2291.

[7] G. Hajj, B. Wilson, B. Iijima, X. Pi, C. Wang, "Analysis of CHAMP ionospheric measurements using a global ionospheric data assimilation model", submitted to proceedings of 1st CHAMP science meeting, GFZ, Potsdam, 22-25 Jan. 2002.

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